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AIR FORCE RESEARCH LABORATORY

Super Cobra (AH-1Z) Human Vibration Evaluation

Suzanne D. Smith

Air Force Research Laboratory

August 2005

Interim Report for March 2005 to August 2005

Human Effectiveness Directorate
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14. ABSTRACT

The purpose of this investigation was to characterize and assess human vibration on board the Super Cobra (AH-1Z) helicopter. The study was conducted to support the U.S. Marine Corp (USMC) H-1 Upgrade Program for the UH-1N Huey and AH-1W Super Cobra, H-1 Crew Environment Survey at the request of the Naval Air Warfare Center Aircraft Division (NAWCAD), Human Systems Division (AIR 4.6). Triaxial acceleration measurements were made on the rigid seat, the interfaces between the occupant and cockpit seat pan and seat back, and on the helmet during selected flight conditions at both the aft and forward seat. The acceleration levels associated with specific frequency components of interest were evaluated. The vibration exposures were assessed in accordance with the International Standards Organization "Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part I: General Requirements (ISO 2631-1: 1997) (1) with regard to comfort and health risk. The results indicated that exposure to vibration during operation of the Super Cobra (AH-1Z) is expected to cause aircrew discomfort to varying degrees. There was some indication that prolonged and repeated exposures may produce the potential for health risk (ISO 2631-1:1997).

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human vibration, acceleration, helicopters, Super Cobra (AH-1Z)

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PREFACE

This report describes the study conducted by the Air Force Research Laboratory, Human Effectiveness Directorate, Biosciences and Protection Division, Biomechanics Branch (AFRL/HEPA), Wright-Patterson AFB, OH, to characterize and assess human vibration on board the Super Cobra (AH-1Z) helicopter. The study was conducted during the period March 2005 to August 2005 to support the U.S. Marine Corps (USMC) H-1 Upgrade Program for the UH-1N Huey and AH-1W Super Cobra, H-1 Crew Environment Survey at the request of the Naval Air Warfare Center Aircraft Division (NAWCAD), Human Systems Division (AIR 4.6). The AFRL Principal Investigator was Dr. Suzanne D. Smith (AFRL/HEPA). Ms. Jeanne A. Smith and Mr. Raymond J. Newman, General Dynamics - Advanced Engineering Services, Inc., Dayton, OH, provided assistance in equipment and instrumentation setup and data reduction. The Primary Point of Contact at NAWCAD was Mr. Sheldon B. Freegard. The tests were conducted at Patuxent River Naval Air Station, MD. The test coordinator at Patuxent River Naval Air Station was Ms. Megan Walsh. The Air Test and Evaluation Squadron Two One (HX21) supported the flight tests and data collection activity.

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SUPER COBRA (AH-1Z) HUMAN VIBRATION EVALUATION

INTRODUCTION

Purpose

The purpose of this investigation was to characterize and assess human vibration on board the Super Cobra (AH-1Z) helicopter. Triaxial acceleration measurements were made on the rigid seat, the interfaces between the occupant and cockpit seat pan and seat back, and on the helmet during selected flight conditions. Data were collected during one flight on the aft seat (pilot) and during two flights on the forward (fwd) seat (copilot). The overall acceleration levels in each direction and the combined-axis accelerations were characterized. In addition, the acceleration levels associated with specific frequency components of interest were evaluated. The vibration exposures were assessed in accordance with the International Standards Organization "Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part I: General Requirements (ISO 2631-1: 1997) (1) with regard to comfort and health risk.

Background

The U.S. Marine Corps (USMC) H-1 Upgrade Program for the UH-1N Huey and AH-1W Super Cobra, H-1 Crew Environment Survey requires the measurement of vibration levels at the pilot and copilot seats to assess the risk of health effects and performance degradation associated with the upgraded helicopters. One modification that was expected to affect the vibration characteristics was the replacement of the two-bladed rotor system in the U.S. Marines' AH-1W Super Cobra attack helicopter to an improved four-bladed configuration. At the request of the Naval Air Systems Command (NAVAIR), Naval Air Warfare Center Aircraft Division (NAWCAD), Human Systems Department (AIR 4.6) , the Air Force Research Laboratory, Human Effectiveness Directorate, Biosciences and Protection Division, Biomechanics Branch (AFRL/HEPA) supported the human vibration evaluation. Due to aircraft availability and scheduling difficulties, the evaluation was limited to the AH-1Z Super Cobra.

The ISO 2631-1: 1997 provides guidelines on the comfort and health risk associated with vibration exposure based on the measurement of triaxial accelerations at the interfaces between the occupant and the seating system. In addition to these measurements, AFRL/HEPA also collected triaxial accelerations on the Thales Avionics' TopOwl helmet-mounted display system flown in the AH-1Z. Although it was desired to collect helmet rotational accelerations, the instrumentation available at the time of the tests would have interfered with the operation of the helmet system. The helmet accelerations were collected to estimate the frequency response of the head/helmet motion relative to the characteristic vibration of the helicopter. These measurements were not intended to evaluate helmet system performance.

METHODS AND MATERIALS

Aircraft Equipment, Test Personnel, and Flight Conditions

The study was conducted on the AH-1Z helicopter (Tail Number 166479, A/C 59003). Two test pilots from the Air Test and Evaluation Squadron Two One (HX21) participated in the study. Test Pilot A weighed approximately 107.5 kg (237 lbs) with a height of approximately 188 cm (6.2 ft). Test Pilot B weighed approximately 72.6 kg (160 lbs) with a height of approximately 167.6 cm (5.5 ft). The flight gear added 9 to 11 kg (20 to 25 lbs) to the pilots' weight during flight. Data were collected during three flights on three separate days (9, 10, 11 March 2005). Pilot A occupied the instrumented aft seat during Flight 1, and occupied the instrumented fwd seat during Flight 2. Pilot B occupied the instrumented fwd seat during Flight 3. During Flight 3, the blades were deliberately placed in an unbalanced condition. Appendix A includes the Super Cobra Test Records listing the ground and flight conditions requested for data collection. The instrumented pilot or copilot was asked to sequentially number the records as they were collected (see below) since the requested flight conditions depended on the particular mission that was flown. Multiple records were collected for some of the flight conditions. For example, during Flight 2, the helicopter landed and took off again with additional records being collected for several conditions.

Vibration Measurement Equipment and Measurement Locations

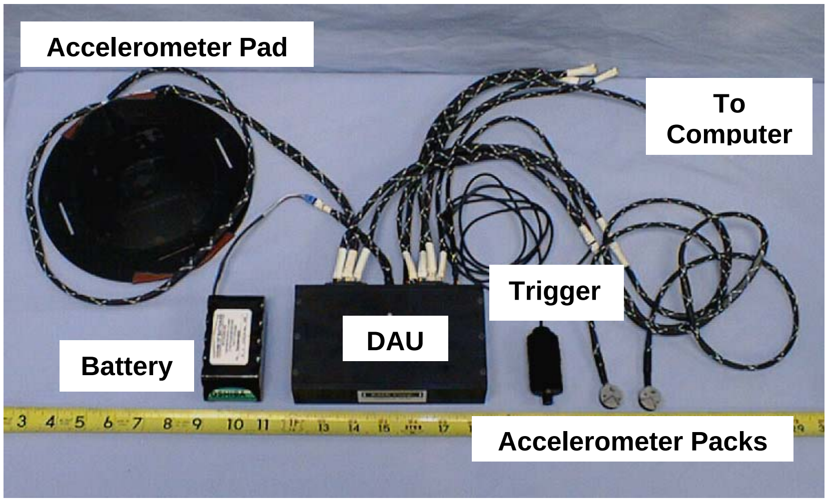
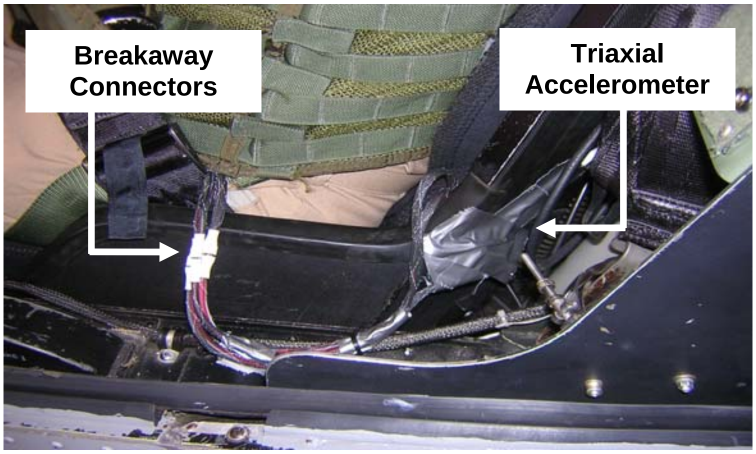


Figure 1. REVER System

The Remote Vibration Environment Recorder (REVER) was used to collect the acceleration data at the selected seat locations and at the helmet. Figure 1 illustrates the components of the REVER system and includes the ancillary instrumentation. The system included a battery-operated 16-channel data acquisition unit (DAU, EME Corporation, Annapolis, MD) measuring approximately 16.5 cm x 10 cm x 4 cm. The DAU enclosure was fabricated using Delrin® and T6-6061 aluminum and provided EMI (electromagnetic interference) shielding. Two types of battery packs were available for use depending on the flight time. The first was rated at 12 volts/2.7 amp-hours and measured approximately 5 cm x 9 cm x 3 cm. The battery operated for up to 2.7 hours. The second was rated at 12 volts/4.0 amp-hours and measured approximately 7 cm x 9 cm x 3 cm. This battery operated for up to 4 hours. The two battery packs were connected to the DAU to extend the operation time. The total system weighed 1.4 kg - 1.6 kg (3.0 – 3.5 lbs) depending on the battery selection. The DAU was located on the inside right pocket of the survival vest during Flight 1, and on the inside left pocket during Flights 2 and 3. This was done to provide easy assess to the computer cable for initial setup and arming of the system just prior to flight. The battery packs were located in the pocket above the DAU.

Figure 2 illustrates the instrumented seat. A triaxial accelerometer pack (Figure 1) was attached to the rigid seat back wing for measuring accelerations in the fore-and-aft (X), lateral (Y), and vertical (Z) directions. The pack was comprised of miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) arranged orthogonally and embedded in a Delrin® cylinder.



a. Seat Accelerometer and Cable Connections

b. Seat Accelerometer Pads (forward seat shown)

Figure 2. Instrumented Seat

The pack measured 1.9 cm in diameter and 0.86 cm in thickness and weighed approximately 5 gm (25 gm with connecting cable). The pack was secured using double-sided mounting tape. As shown in Figure 2a, the seat back wing was oriented approximately 45 degrees from the seat back. The coordinate system was relative to the seated occupant. Therefore, the measured horizontal accelerations were transposed into the occupant coordinate system. For the actual flight, the cable from the seat accelerometer pack was further secured directly to the seat frame via a lanyard. Although not shown, one accelerometer pack was attached to a flat section of the helmet back along the back centerline using double-sided mounting tape. The flat section was oriented approximately vertical when the head was in the upright posture. The accelerometer cable ran along the back lower edge of the helmet, over the right (aft seat) or left (fwd seat) shoulder, and down the front of the vest where it connected to the DAU cable located on the inside of the vest. Duct tape was used to secure the cable to the helmet. Accelerometer pads were used to measure the vibration transmitted to the occupant via the seat pan and seat back in accordance with ISO 2631-1: 1997 (1) (Figure 2b). Each pad consisted of a flat rubber disk measuring approximately 20 cm in diameter and weighing 355 gm (with connecting cable). A triaxial accelerometer pack was embedded in the disk. The pads were attached to the seat pan and seat back cushions using double-sided adhesive tape and duct tape. Cable connections between the accelerometers and DAU were made via breakaway connectors (Figure 2a) that required less than 21.8 N to separate. Pre- and post-calibrations were conducted on all accelerometers. For the calibrations, the comparison method was used with an accelerometer traceable back to the National Institute of Standards and Technology (NIST).

Data Collection and Processing Methods

The triggering device (Figure 1) weighing 20 gm and measuring approximately 7.6 cm in length and 2.2 cm in diameter was used to initiate the data collection during a specified flight condition. The DAU was set up to automatically collect simultaneous data from all channels for 20 seconds upon pilot or copilot initiation. Each 20-second data segment defined a test record associated with a specified flight condition. The acceleration data were low-pass filtered at 250 Hz (anti-aliasing) and digitized at 1024 samples per second. The digitized data were downloaded onto a computer at the end of each flight.

Each resultant acceleration time history associated with each test record or data segment was processed to estimate the constant bandwidth power spectral density (psd) using the MATLAB® Signal Processing Toolbox (The MathWorks, Inc., Natick, MA). Welch's method (3) was used to divide the signal into 2-second sub-segments with 50% overlap. A Hamming window was then applied to these segments, and the resultant power spectral densities were averaged for each 20-second period. The root-mean-square (rms) acceleration levels, a_{rms}, were calculated from the following relationship:

$$a_{rms_i} = \sqrt{(a_{psd_i} * 0.5)} \qquad 1$$

where i represents the ith frequency component, a_{psdi} is the acceleration power spectral density at frequency i, and 0.5 is the frequency resolution in Hertz (Hz). The constant bandwidth data were specifically used to evaluate the frequency location of acceleration peaks.

The acceleration time history segments were also analyzed in one-third octave proportional frequency bands using a software program developed by Couvreur (2). One-third octave frequency bands are typically used to assess human vibration exposure in accordance with ISO 2631-1: 1997 as described in detail below. The program uses MATLAB® routines to generate the rms acceleration level in each one-third octave band (reported at the center frequency) in each direction. The program was modified to include frequencies below 25 Hz.

The overall rms acceleration level between 1 and 80 Hz, *a*, in each direction (X, Y, and Z) for each data record or segment was calculated as:

$$a = \left[\sum_i a_i^2 \right]^{\frac{1}{2}} \qquad 2$$

where a_i is the rms acceleration level associated with the *ith* frequency component (in 0.5-Hz increments for constant bandwidth analysis, and at the center frequency of the one-third octave frequency band for proportional bandwidth analysis) in the specified direction. Both analysis methods will result in approximately the same overall rms acceleration level between 1 and 80 Hz. In this study, the overall rms accelerations were calculated from the one-third octave data. The combined-axis overall acceleration level, a_{xyz}, was calculated from the one-third octave overall acceleration levels as:

$$a_{xyz} = \sqrt{a_x^2 + a_y^2 + a_z^2} \qquad 3$$

where a_x, a_y, and a_z are the overall accelerations in the X, Y, and Z directions, respectively.

The assessment of comfort reaction and health risk in accordance with ISO 2631-1: 1997 requires the application of frequency weightings and multiplying factors representing equal human sensitivity. Table 1 lists the frequency weightings and multiplying factors used to assess comfort reaction and health risk depending on the location and direction of the measurement. Figure 3 illustrates the frequency weightings W_d, W_k, and W_c for comparison.

Table 1. Frequency Weightings and Multiplying Factors (ISO 2631-1: 1997 (1))

	HEALTH RISK Seat Pan		COMFORT REACTION Seat Pan		Seat Back	
Direction	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor
X	W_d	k = 1.4	W_d	k = 1.0	W_c	k = 0.8
Y	W_d	k = 1.4	W_d	k = 1.0	W_d	k = 0.5
Z	W_k	k = 1.0	W_k	k = 1.0	W_d	k = 0.4

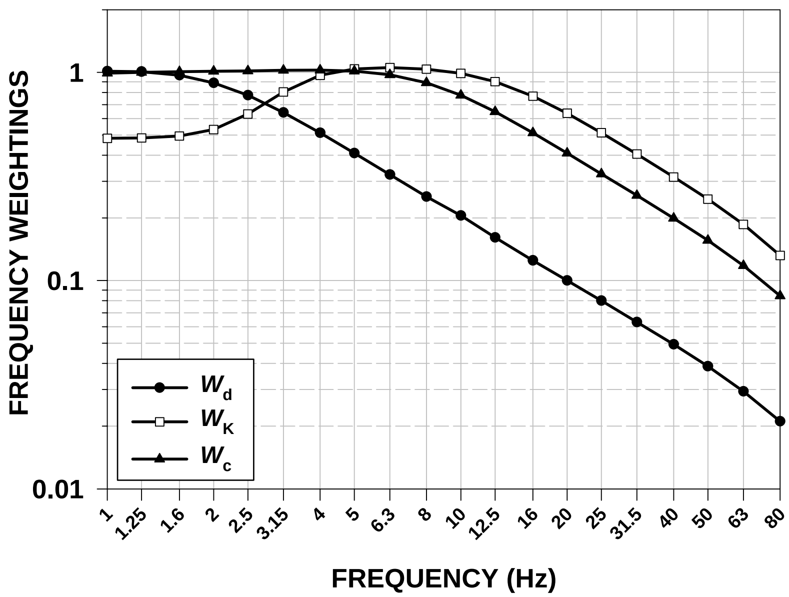


Figure 3. Frequency Weightings W_d, W_k, and W_c (ISO 2631-1: 1997 (1))

The overall weighted rms acceleration level (a_w) at the seat pan and seat back in each axis (X, Y, and Z) was calculated between 1 and 80 Hz as:

$$a_w = \left[\sum_i W_{ji}^2 a^2 rms_i \right]^{1/2} \qquad 4$$

where j represents the particular frequency weighting (d, k, or c, Figure 3) depending on the measurement site and direction (Table 1), and i represents the ith frequency component (at the center frequency of the one-third octave frequency band). The combined-axis overall weighted acceleration level, a_{wxyz}, was calculated from the one-third octave overall weight acceleration levels as:

$$a_{wxyz} = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2} \qquad 5$$

where a_{wx}, a_{wy}, and a_{wz} are the weighted overall accelerations in the X, Y, and Z directions, respectively, and k_x, k_y, and k_z are the multiplying factors defined in Table 1. This value is known as the point vibration total value (VTV) and was calculated at both the seat pan and seat back for the assessment of comfort (noting that k =1 for all three directions). The overall unweighted and weighted seat pan and seat back acceleration levels in each direction are reported (Eqs. 2 and 4, respectively) for selected flight conditions. The overall vibration total value (VTV) for comfort was calculated from the root sum-of-squares of the point VTVs from the seat pan and seat back and compared to the comfort reactions given in ISO 2631-1: 1997. For assessing health, the VTV at the seat pan was used (Eq. 5) and compared to the Health Guidance Caution Zones given in ISO 2631-1: 1997.

RESULTS

General Observations of the Time Histories and Overall Acceleration Levels

A cursory review of the time histories and the overall acceleration levels showed that the highest vibration occurred during Dive. For some flight conditions, there was variability between time history records that could be explained by the characteristics of the maneuver at the time the records were taken. For example, during Flight 1 and 2 with Pilot A, two records were taken during both the Normal and Steep Approaches, respectively. The first record captured "entry from base leg to final," while the second record captured "descent to hover." During the first flight, the "descent to hover" tended to show higher overall acceleration levels for both types of approaches. For the second flight, the Normal Approach showed this tendency, but the Steep Approach showed the opposite trend. This may have been due to the timing of the initiation of data collection during the maneuver.

With regards to the effect of airspeed during Level Flight, there appeared to be differences in the overall acceleration levels at the rigid seat that were associated with the seat location. During Flight 1, with Pilot A in the aft seat, the highest vibration tended to occur in the Y direction. There was no clear effect of airspeed on the overall acceleration levels in the three directions. During Flights 2 and 3, where the measurements were made at the fwd seat, the highest vibration tended to occur in the X direction. During these two flights, the highest vibration, regardless of direction, occurred with an airspeed of 60 Knots Calibrated Airspeed (KCAS) Maximum Endurance. As airspeed increased up to 140 KCAS, the vibration level tended to decrease or show no clear differences. The vibration levels at maximum air velocity in Level Flight (V_H) tended to be higher than the levels at 140 KCAS, particularly in the X direction.

Characteristics of AH-1Z Super Cobra Frequency Response Spectra

All figures referenced in the RESULTS are located in Appendix B. Figure B-1 illustrates the acceleration frequency spectra measured at the rigid seat, seat pan, seat back, and helmet during Flight 1 for the level flight condition at 3000 ft and 140 KCAS. Both the 0.5 Hz constant bandwidth (Figure B-1a) and one-third octave (Figure B-1b) data are shown. The figures show distinct peaks or peak regions that, to varying degrees, were common among all flight conditions. In the constant bandwidth data (Figure B-1a), peaks were observed at 5 Hz, 10 Hz, 19.5 Hz, 25 Hz, and at multiples of 19.5 Hz. The 5 Hz peak was associated with the main rotor speed of the aircraft (296 RPM or 4.9 Hz). The 19.5 Hz peak was associated with the blade passage frequency (4 X 296 = 1184 or ~19.7 Hz). The 10 Hz peak coincided with the two per rev (2p) frequency. However, there was some speculation that this peak may have been due to a resonance in the tail boom or even some other source. The 25 Hz coincided with the five per rev (5p) frequency. As with the 10 Hz vibration, the source of the 25 Hz vibration was not clear. This peak, when present, occurred primarily in the lateral (Y) direction of the aircraft during flight, but was observed during the ground runs in all three directions. The tail rotor speed was approximately 1307 RPM or ~21.8 Hz. It was not clear if the tail rotor contributed to any of the peak behavior observed at the cockpit seat locations. In the one-third octave data (Figure B-1b), the peaks were broader, as expected, due to the processing technique. Peaks were observed in the vicinity of 5 Hz, 10 Hz, 20 to 25 Hz, and at multiples of 20 Hz. Helicopter maneuvering or environmental conditions most likely contributed to the lower frequency vibration (below 5 Hz) observed in both the constant bandwidth and one-third-octave bandwidth data.

Figure B-1 shows that very little vibration was transmitted to the helmet above 10 Hz. The constant bandwidth spectra particularly showed substantial helmet vibration associated with the rotor speed (5 Hz) and the two per rev vibration (10 Hz) depending on the direction. Lower frequency vibration below 5 Hz was also evidenced and, again, may have been associated with aircraft maneuvering causing involuntary head motion, as well as pilot-induced voluntary head motion occurring as part of normal operations. It is cautioned that the attitude of the head during the collection of data was not known. It was expected that the measured vibration at the back of the head included rotational motions of the head at these low frequencies.

Propulsion-Related Spectral Response Characteristics

Throughout the remainder of this report, selected flight conditions from the test records were used to evaluate the vibration. These flight conditions were selected based on their levels of vibration, as well as the assumption that these flight conditions provided a good representation of the vibration levels expected during normal operations for prolonged periods (such as Level Flight) as well as tactical and strategic maneuvers (such as Dive). As mentioned above, distinct peaks were observed in the spectral data that were associated with the propulsion system of the helicopter. The frequency distribution and the direction of the vibration are very important when considering the effects on human vibration sensitivity as described in the following sections. This spectral information is lost when evaluating the overall acceleration levels and the overall combined-axis vibration. This section focuses on summarizing the characteristics of the seat vibration at 5, 10, and 19.5 Hz in the three orthogonal directions. Figures B-2 and B-3 illustrate the mean rigid seat and seat pan multi-axis rms acceleration levels +/- one standard deviation, respectively, in the X, Y, and Z directions at these frequencies. The Level Flight condition included one record at each of the four airspeeds for each flight to obtain the mean value. Hover-OGE included four records from each flight for calculating the mean value. Only one record was recorded during Dive during each flight. Both the Steep Approach and Normal Approach included two records each per flight. Although not shown, the seat back rms accelerations showed trends that were similar to those observed at the seat pan with regards to the frequency and direction of the vibration. In order to visualize increases or decreases in the transmission of vibration from the rigid seat to the seated occupant, the transmissibility was calculated as the ratio between the seat pan rms acceleration and rigid seat acceleration in each respective direction at each respective frequency. This calculation compares the output motions at the seat pan with the input motions at the rigid seat without considering any linear causal relationships between the two. Emphasis was placed on the actual vibration measured at the seat pan relative to the rigid seat. Figure B-4 illustrates the mean seat pan transmissibility +/- one standard deviation at each of the selected frequencies for the three flights. All three flights showed that Dive produced notable seat vibration in the vertical (Z) direction at 5 Hz (rotor speed) (Figs. B-2 and B-3). The vertical vibration was higher at the fwd rigid seat (Flights 2 and 3) as compared to the aft rigid seat (Flight 1) during Dive (Figure B-2). In addition, the fwd rigid seat showed higher levels of fore-and-aft or X-axis vibration at 5 Hz during Dive (Figure B-2). The vertical vibration was also higher at the fwd seat pan (Flights 2 and 3) as compared to the aft seat pan (Flight 1) (Figure B-3). However, in contrast to the rigid seat, the fore-and-aft vibration at the seat pan was reduced. The transmissibilities illustrated in Figure B-4 confirm the reduced transmission of the fore-and-aft vibration at the fwd seat pan at 5 Hz during Dive (magnitude ratio < 1.0). Figure B-4 also shows damping of the fore-and-aft vibration at the fwd seat pan during Flights 2 and 3 at 5 Hz for several other flight conditions (magnitude ratios < 1.0). Although not shown, the fore-and-aft vibration at 5 Hz was also slightly damped at the seat back at the fwd seat. One notable difference between the aft and fwd seat was the increased transmission of the 5 Hz vibration at both the seat pan and seat back in the lateral direction for most of the flight conditions during Flights 2 and 3. This is dramatically seen in Figure B-4 for the fwd seat pan transmissibilities during Flights 2 and 3 at 5 Hz (magnitude ratios > 1.0).

The one distinct characteristic of the vibration levels occurring at 10 Hz was the higher lateral (Y) and vertical (Z) accelerations observed at the fwd rigid seat (Flights 2 and 3) as compared to the aft rigid seat (Flight 1), particularly for Level Flight and Dive (Figure B-2). The figures do show that there were substantial variations in the vibration levels observed during Level Flight at 10 Hz (noting the large standard deviations). The lateral and vertical vibration levels were damped to various degrees at the seat pan and seat back for all three flights (with the exception of the vertical vibration at the aft seat pan), but were particularly marked for Dive, as illustrated in Figure B-4 at 10 Hz.

At 19.5 Hz (Blade Passage Frequency), all three flights showed some damping of the fore-and-aft vibration at the seat pan and seat back as illustrated in Figure B-4 for the seat pan. For the fwd seat, there was substantial damping of both the lateral and vertical vibration at the seat pan during Dive (Figure B-4). Although Figure B-4 shows a substantial increase in the lateral seat pan transmissibility at 19.5 Hz during Level Flight in the fwd seat (Flights 2 and 3), the associated vibration at the rigid seat was relatively low (Figure B-2). This was also the case for the lateral vibration during the Normal Approach for Flight 3; the associated vibration at 19.5 Hz was relatively low at the rigid seat (Figure B-2).

Psychophysical Effects

The one-third octave rms accelerations were weighted in each direction relative to human sensitivity as defined in ISO 2631-1: 1997 (1), Table 1, and Figure 3. These weightings imply that accelerations with similar weighted values would be equal with regard to human sensitivity, and that higher weighted values would be perceived as being the highest vibration. Figures B-5 and B-6 illustrate the mean unweighted and weighted seat pan and seat back rms accelerations, respectively, +/- one standard deviation in each direction for the selected flight conditions. The weighted values also incorporate the multiplying factors given in Figure 3 for the respective location and direction of the vibration. All records were used for Level Flight. For Level Flight, there were four records for Flight 1, eight records for Flight 2, and nine records for Flight 3. For all flights, there were four records for Hover-OGE, one record for Dive, two records for the Steep Approach, and two records for the Normal Approach, as described previously. Even though the unweighted vibration levels in the horizontal plane of the seat pan were similar to the levels in the vertical direction for many of the flight conditions (Figure B-5a), all selected flight conditions for all three flights distinctly indicated that the vibration in the vertical direction would dominate the perception of the vibration at the seat pan and have the greatest influence on comfort (Figure B-5b). In contrast, at the seat back, the tendency was for higher perception of vibration in the fore-and-aft (X) direction (Figure B-6b). Comparing Figures B-5b and B-6b for the weighted values, the motions at the seat pan would have the greater influence on the perception of the helicopter vibration.

Vibration Exposure Assessment (ISO 2631-1: 1997)

Comfort Reaction

For the assessment of comfort reaction, the point VTVs from the seat pan and seat back were combined. Figure B-7 illustrates the overall point VTVs for all selected conditions described above for the three flights. Since the comfort reactions are not time-dependent (ISO 2631-1: 1997), even the short exposures expected during Dive are included in the assessment. All three flights showed that all of the selected conditions would be associated with some discomfort (Little Uncomfortable) according to the standard, with Hover-OGE showing instances of not being uncomfortable. For all three flights, the assessment indicated that Dive would produce the most discomfort. The associated vibration would be considered Very Uncomfortable for Flights 1 and 3, and Uncomfortable for Flight 2. The Steep Approach showed instances of being Fairly Uncomfortable to Uncomfortable. During Level Flight, where the longest exposures are expected to occur during operations, all recorded exposures were assessed as being a Little Uncomfortable to Fairly Uncomfortable. For one record during Flight 2, the VTV indicated that the exposure would be considered Uncomfortable. Figure B-8 illustrates the mean comfort reactions plus one standard deviation among the flights for the selected flight conditions and can be used as a general guideline for comfort assessment during Super Cobra operations based on the data collected in this study.

Health Risk

Figure B-9 illustrates the Health Guidance Caution Zones given in ISO 2631-1: 1997. Included are the VTVs for all Level Flight seat pan data from all three flights using Equation 3 and the appropriate weighting curves and factors. Unlike the Comfort Reactions, time durations are given for Health Risk. The Level Flight data were used based on the assumption that any prolonged exposures would best be represented by these data. The data include four records from Flight 1, eight records from Flight 2, and nine records from Flight 3. VTVs occurring below the lower line or below the zone of the Health Guidance Caution Zones (dashed lines) are considered to have low risk of producing any health effects. VTVs that fall between the two zone lines (dashed lines) or in the zone require caution since this region indicates a potential for health risk. VTVs occurring above the upper line or above the zone do indicate a likelihood for health risk. The health risks have primarily been associated with injury to the lumbar spine and connected nervous system (ISO 2631-1: 1997). The worst case for health risk occurred during Flight 2 for Level Flight at 3000 ft and 60 KCAS Maximum Endurance. During this exposure, relatively high acceleration levels were observed compared to the acceleration levels measured during Level Flight at other airspeeds and those measured during Flights 1 and 3. For prolonged exposure at this acceleration level, the zone (potential health risk) would be reached in about 2 to 2.5 hours. The exposure was above the zone (health risk likely) at around 8 hours of exposure. During Flight 3, two exposures exceeded VTVs of 0.63 ms^{-2} rms and would reach the lower line or zone at 3 hours and the upper zone at about 10 hours. Those VTVs falling just below 0.63 ms^{-2} rms during Flight 3 would reach the zone between 4 and 4.5 hours of exposure and would cross into the upper zone where health risks are likely in about 15 hours. It is expected that any mission would include a combination of level flight at varying airspeeds and some shorter duration exposures to flight conditions that have relatively high levels of vibration. Figure B-10 depicts the mean Level Flight VTVs +/- one standard deviation (represented by the white bar) based on all of the Level Flight data collected among the three flights. This figure can be used as a guideline for predicting potential health risk during Super Cobra operations based on the data collected in this study.

DISCUSSION

This study characterized and assessed the multi-axis vibration on board the Super Cobra AH-1Z. Triaxial accelerations were collected at the rigid seat and at the interfaces between the pilot or copilot and the seating surface, i.e., the seat pan and seat back, and at the helmet. These measurements were made to quantify the vibration actually transmitted to the occupant and for assessing the effects of the vibration on the comfort and health risk to the aircrew during operations. Since the frequency spectra of both fixed- and rotary-wing aircraft show distinct peaks associated with the propulsion system, the acceleration levels associated with the lower frequency spectral components were investigated, including the transmission of this vibration to the occupant from the rigid seat. It was assumed that the acceleration measurements made at the rigid seat closely represented the vibration generated by the helicopter that entered the seating system.

The human body is very sensitive to low frequency vibration below 10 Hz. When exposed to structure-borne vibration, there is a whole-body resonance observed usually between 4 and 8 Hz (7), where the transmission of vibration is amplified in the body. The rotor speed of the Super Cobra coincides with this critical frequency range. In addition, the helicopter also showed a two per rev (2p) peak at 10 Hz. In addition to the obvious issue with vibration exposure in the lower frequency range, recent investigations onboard fixed-wing propeller aircraft have raised questions about the potential effects of higher frequency vibration on aircrew comfort, fatigue, performance, and even health (4, 5). This would include the blade passage frequency of the Super Cobra (observed at 19.5 Hz), multiples of the blade passage frequency, and the five per rev (5p) vibration observed in some instances at 25 Hz.

Figures B-2 – B-4 emphasized the effect of the vibration frequency, direction, and seat transmission characteristics of the Super Cobra seating system based on several flight conditions. In some cases, the seat cushions appeared to amplify the transmission of vibration to the occupant (noted in the increased transmission of lateral vibration at the seat pan at 5 Hz, Figure B-4)), while in other cases the cushions appeared to dampen the vibration (noted in the fore-and-aft vibration at the seat pan at 19.5 Hz, Figure B-4). If the vibration that is being amplified is substantial, then strategies should be considered that reduce these levels.

The development of specific strategies for reducing vibration and the assessment of the effects of the vibration on the occupant become a bit complicated when considering the psychophysical effects of vibration on human perception. The best example of the impact of the psychophysical effects is shown in Figure B-5. Once the acceleration levels were weighted in accordance with the guidelines given in ISO 2631-1: 1997 (Table 1 and Figure 3), the ability of the seat pan cushion to amplify or even dampen the horizontal vibration was minimized by the high perception of vertical vibration among all of the flight conditions. This is easily explained when considering the frequency weighting and multiplying factors used to obtain these weighted values. The weighting for the seat pan vertical vibration (W_k) in Figure 3 has much less effect on the actual measured accelerations occurring above 2 Hz as compared to the weighting for the seat pan horizontal vibration (W_d). The frequency weightings (W_c and W_d) and multiplying factors for the seat back resulted in very little contribution of the seat back accelerations to the perception of the vibration. This study investigated the overall weighted acceleration levels as described in the standard. However, a comparison of the individual weighted frequency components of concern in the Super Cobra could further delineate the focus for developing new mitigation strategies.

One of the major objectives of this study was to assess the effects of the vibration onboard the Super Cobra (AH-1Z) on aircrew comfort and health risk in accordance with the current ISO 2631-1: 1997. This international standard is also recommended in the MIL STD 1472F (6). As shown in Figures B-7 and B-8, the vibration generated in the Super Cobra during flight would present varying degrees of discomfort to the pilot and copilot. It is unfortunate that this assessment does not provide guidelines on the effect of the vibration on fatigue and performance. Even though the ISO 2631-1:1997 comfort reactions have no time dependency, it is speculated that prolonged exposures to this vibration would cause fatigue that could lead to performance degradation. This would certainly depend on the workload demands. The Super Cobra AH-1Z was designed to be an attack helicopter and, therefore, the workload demand would be relatively high. In addition, it is expected that those maneuvers producing high levels of discomfort, such as Dive, Steep Approach, and Level Flight at maximum speed, would be more prevalent during these missions.

When considering the workload demands of the Super Cobra, the aircrew are also using a helmet-mounted display and targeting system. Figure B-1 indicates that low frequency vibration is transmitted to the head during operations. There are some potential issues that should be realized with regards to the helmet-mounted equipment. Low frequency vibration has been associated with longer than desired lock-on times in helmet-mounted targeting systems (7). At low frequencies where head rotations can occur, the vestibular ocular reflex acts to stabilize the line-of-sight between the eye and a viewed object by rotating the eye in the opposite direction. This compensatory eye movement becomes less effective in stabilizing images moving with the head at low frequencies (<20 Hz), causing the potential for visual blurring when using a helmet-mounted display (7, 8).

The health risk assessment conducted in this study was based on the Level Flight data collected among the three flights. The mean data depicted in Figure B-10 shows that, based on these data, the zone for potential health effects would be reached in approximately 6 hours. This time would be shortened or lengthened depending on the particular demands of the mission, as seen in the individual data depicted in Figure B-9. During daily tactical operations, caution should be considered based on the data presented in Figure B-10. Historically, the major health risk to helicopter pilots has been low back pain or low back injury during prolonged and repeated exposures to operational vibration. However, other factors can also influence these symptoms, including sitting in one position with less than optimum posture for long periods of time. In addition to the issue of back pain and back disorders, there have been increasing anecdotal reports of buttocks and lower extremity numbing during prolonged operations in both fixed- and rotary-wing aircraft where the aircrew has little opportunity to change sitting position or posture. The extent of these symptoms among the DoD operational community has not been determined and, therefore, the health risks are currently unknown. However, these symptoms could have the potential of increasing discomfort, causing fatigue, affecting performance, and creating a safety hazard. The occurrence and mechanisms of these symptoms should be a top priority for DoD research laboratories.

CONCLUSIONS

1. Exposure to vibration during operation of the Super Cobra (AH-1Z) is expected to cause aircrew discomfort to varying degrees in accordance with the current guidelines for assessing human vibration exposure. Although guidelines are not given on the effect of these exposures on fatigue and performance, caution should be taken when considering tactical operations in hostile environments over long periods of exposure.

2. There is also an indication that prolonged and repeated exposures to Super Cobra (AH-1Z) vibration may produce the potential for health risk, although these risks are not easily defined at

this time and depend on the specific demands of the mission. Again, caution should be taken when considering tactical operations conducted on a regular basis for prolonged periods of time.

3. The evaluation of any issues with helmet-system targeting during tactical activity or the occurrence of visual blurring when using the helmet system should consider the potential influence of low frequency aircraft vibration.

4. It is imperative that aircrews be diligent in reporting any persistent discomfort, back pain, numbing, and noticeable fatigue or performance degradation to their medical flight personnel and other appropriate individuals. The documentation of these symptoms should be made a high priority no matter how minor they may appear. The documentation of these symptoms is critical for developing mitigation strategies, improving flight equipment, and insuring the optimum safety of the warfighter.

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APPENDIX A

Super Cobra Test Records

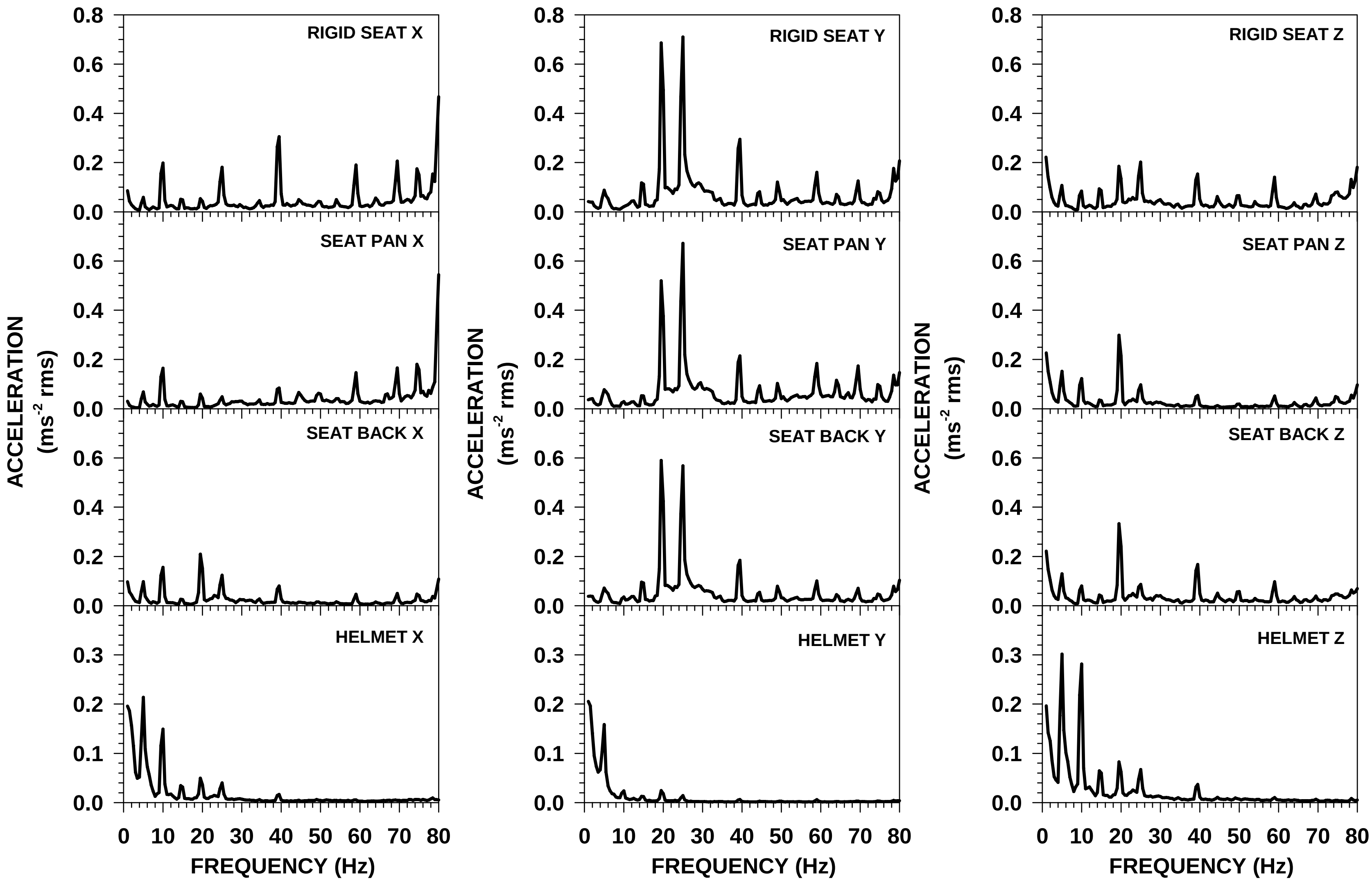
SUPER COBRA TEST RECORDS *Multiple Records if possible

CONDITION	**ALT (ft MSL)**	**A/S (KCAS)**	**COMMENTS** (Wind, etc.)
A. Ground run	0	0	
Record #:			
B. Lift Off to IGE Hover	0-50	0	
Record #:			
C. Hover Taxi*	0	A/R	
Record #:			
D. Take Off*			
Record #:			
E. Hover – OGE*	30-100	0	
Record #:			
F. Climb*	3000	A/R	
Record #:			
G. Level Flight*	3000	60	Max Endurance
Record #:			
H. Level Flight*	3000	90	
Record #:			
I. Level Flight*	3000	140	
Record #:			
J. Level Flight*	3000	V_H	
Record #:			
K. Dive	3000	V_{ne}	
Record #:			
L. Rearward Flight	30	20	IGE
Record #:			
M. Sideward Flight	30	30	IGE
Record #:			
N. Steep Approach*			
Record #:			
O. Normal Approach*			
Record #:			
P. Landing	0	0	
Record #:			

MSL: Mean Seat Level
KCAS: Knots Calibrated Air Speed
IGE: In ground effect
OGE: Out of ground effect
V_H: Maximum air velocity in level flight
V_{ne}: Velocity not to exceed

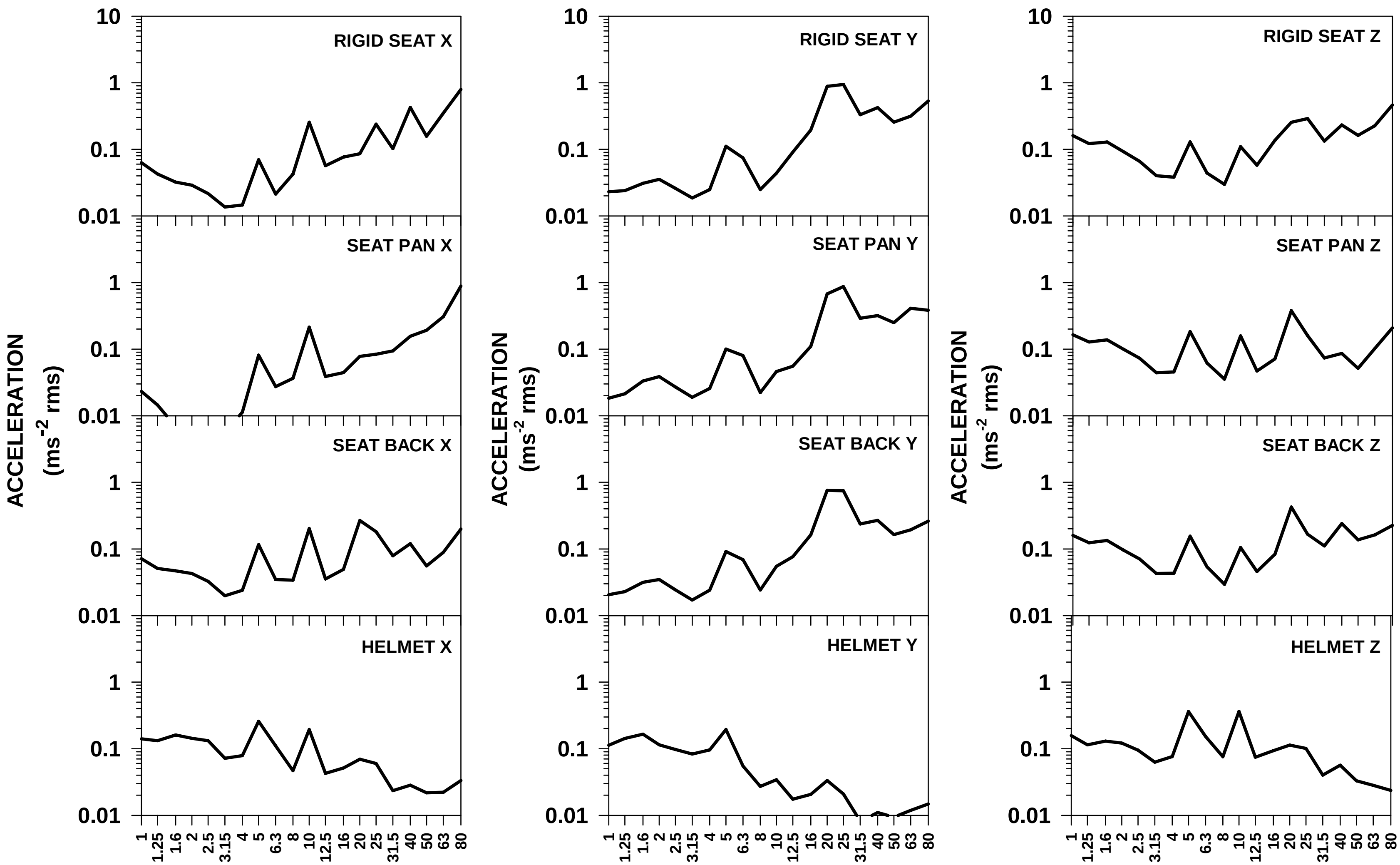
APPENDIX B

Figures



a. Constant Bandwidth Spectra (0.5 Hz Resolution)

Figure B-1. Seat Pan and Seat Back Acceleration Frequency Spectra



b. One-Third Octave Spectra

Figure B-1. Seat Pan and Seat Back Acceleation Frequency Spectra (Continued)

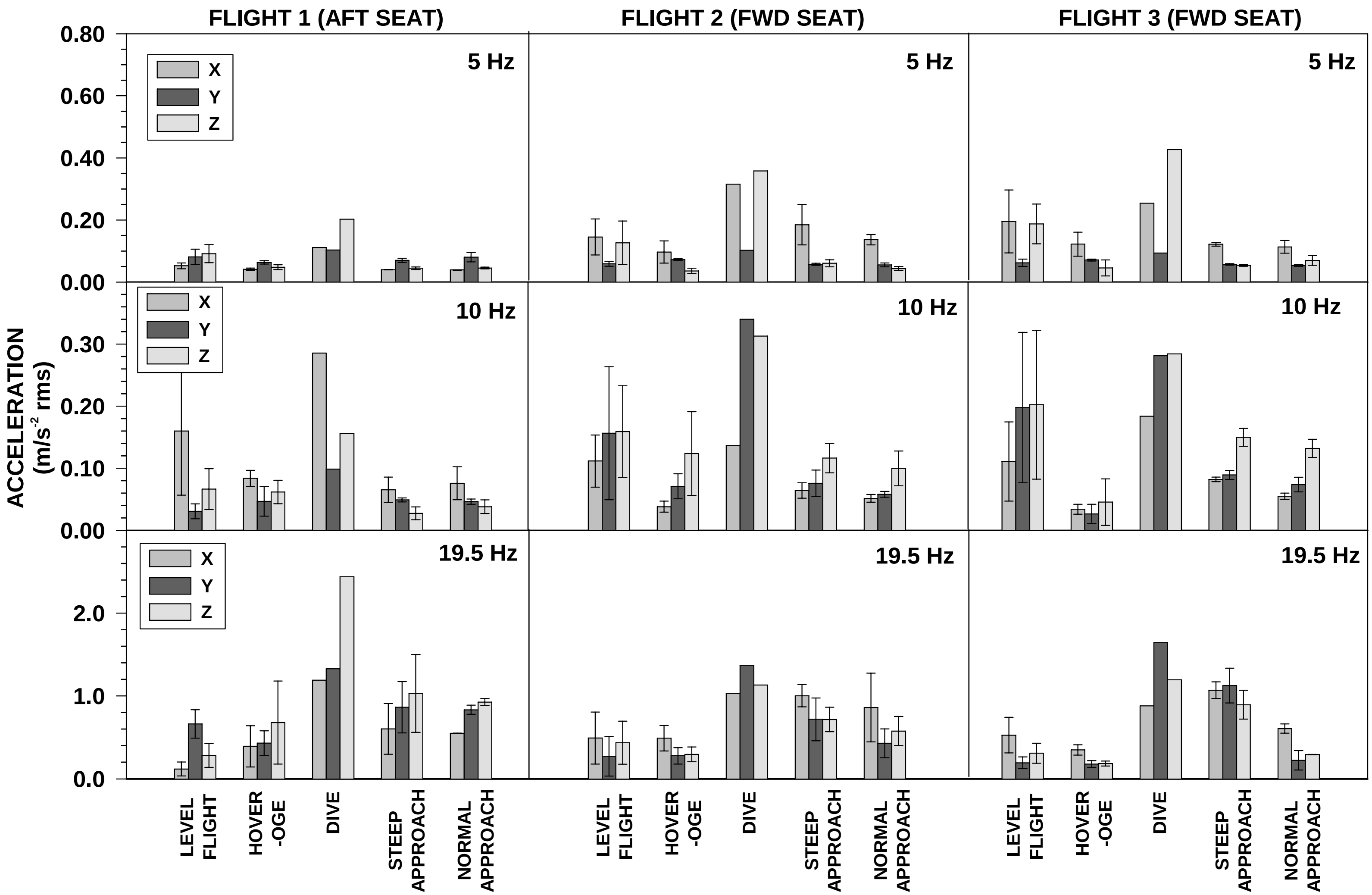


Figure B-2. Mean Rigid Seat Multi-Axis Rms Acceleration +/- One Standard Deviation at 5 Hz, 10 Hz, and 19.5 Hz

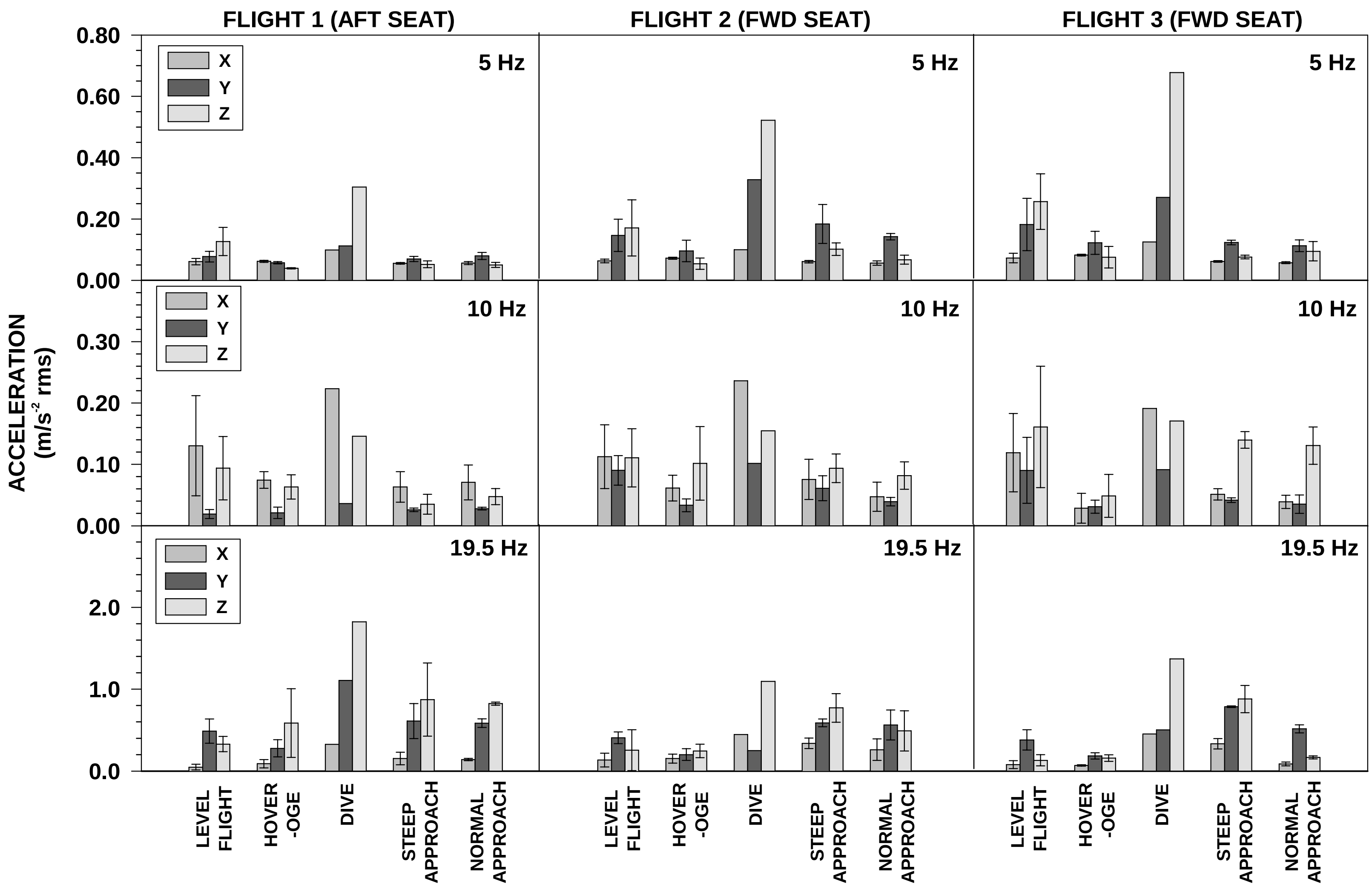


Figure B-3. Mean Seat Pan Multi-Axis Rms Acceleration +/- One Standard Deviation at 5 Hz, 10 Hz, and 19.5 Hz

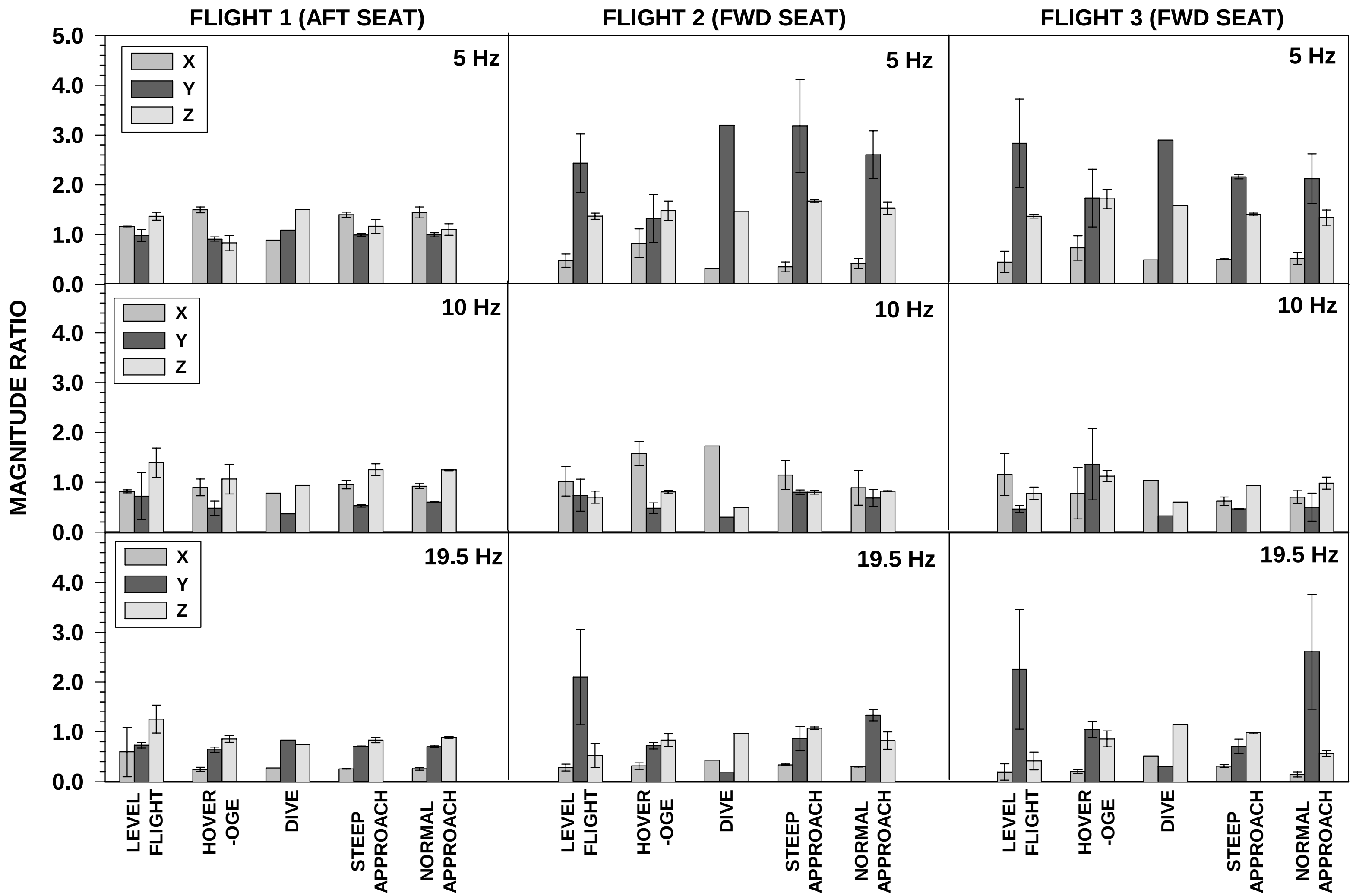
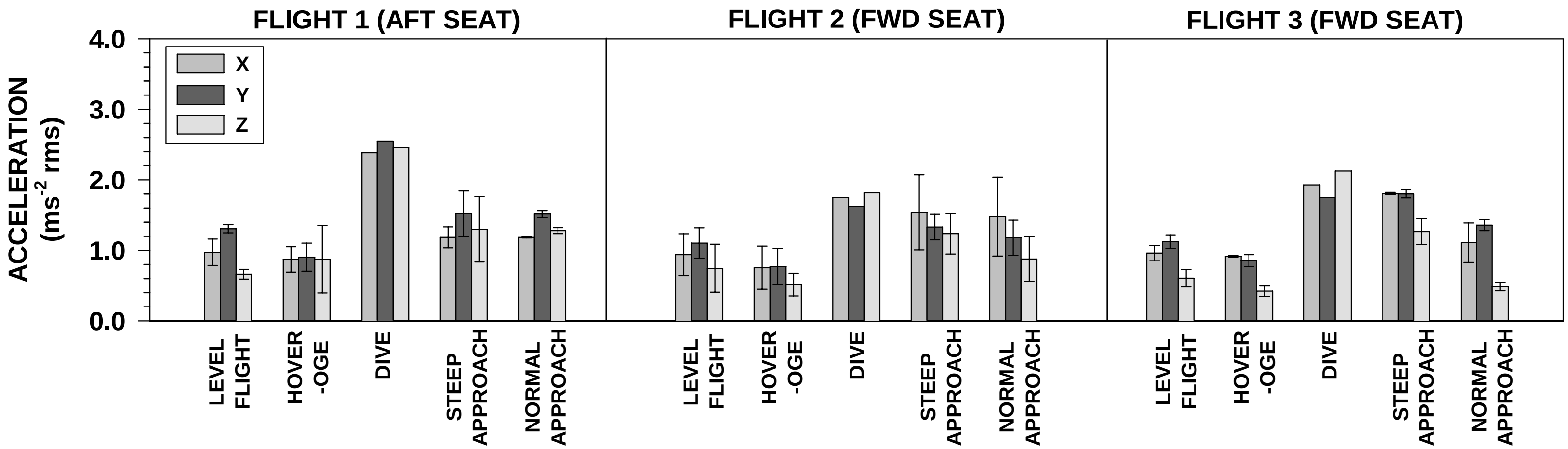
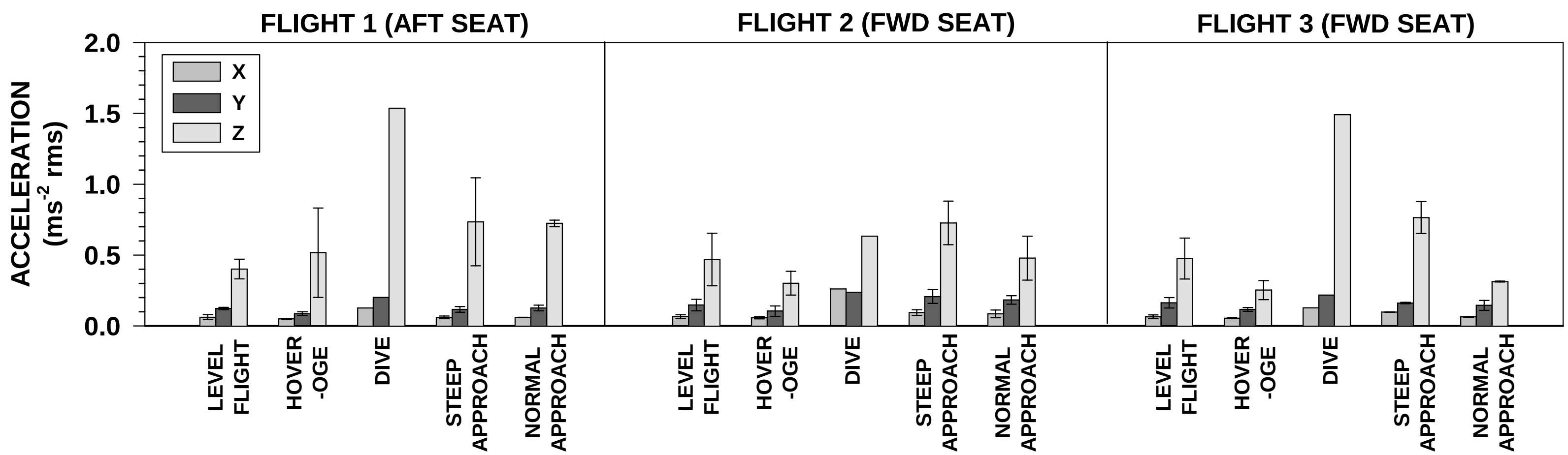


Fig B-4. Mean Seat Pan Transmissibilities +/- one One Standard Deviations at 5 Hz, 10 Hz, and 19.5 Hz

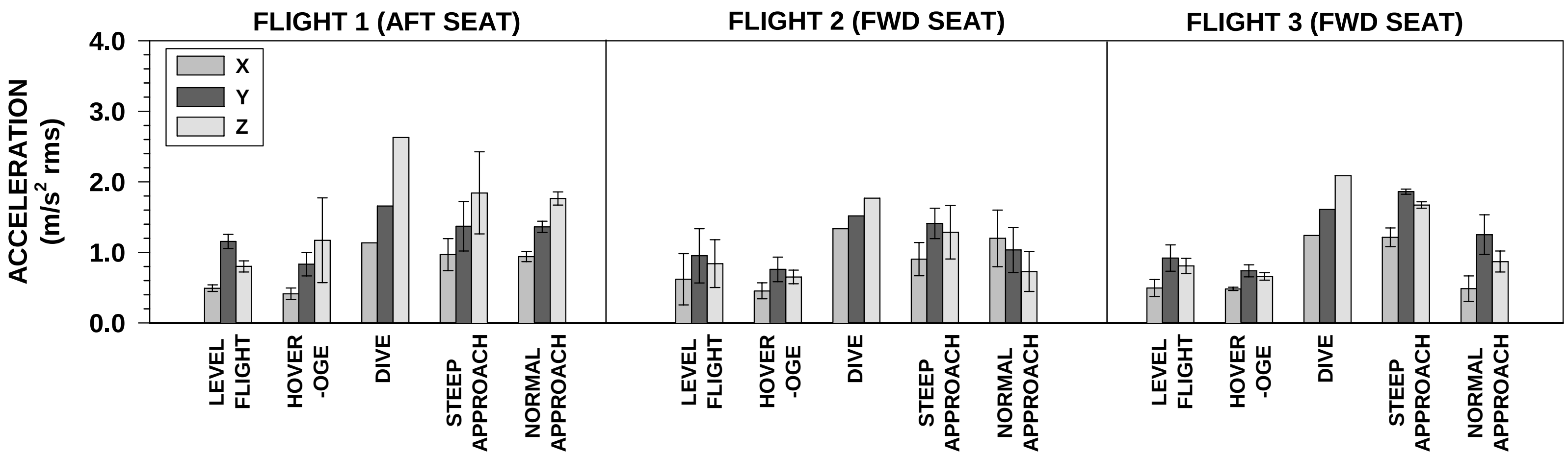


a. Unweighted

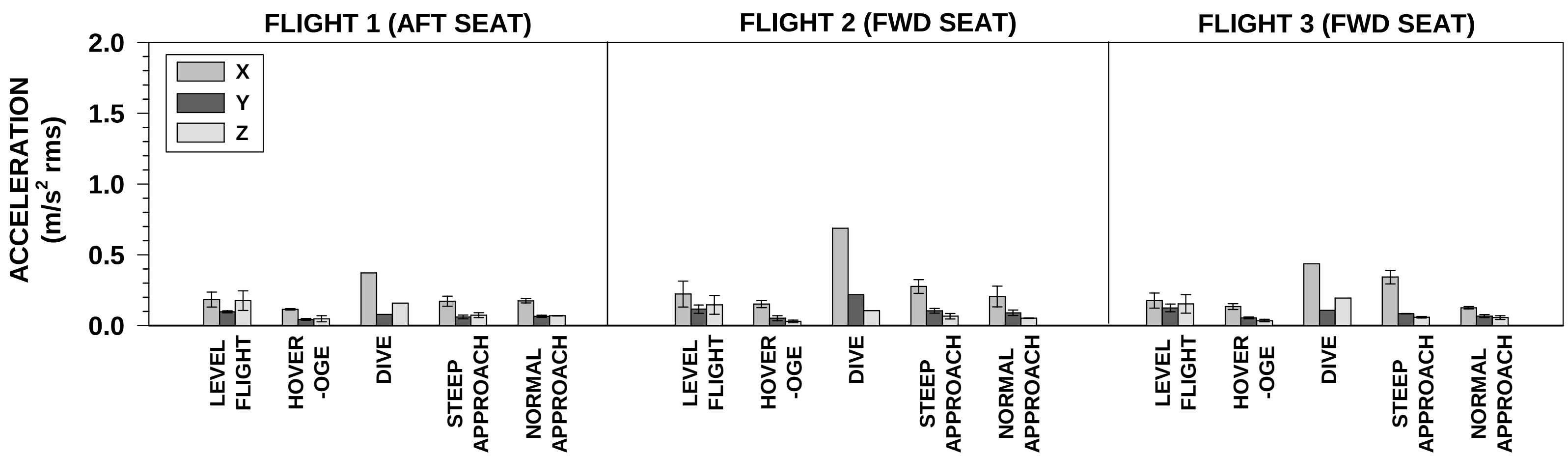


b. Weighted

Figure B-5. Mean Unweighted and Weighted Seat Pan Overall Rms Acceleration +/- One Standard Deviation



a. Unweighted



b. Weighted

Figure B-6. Mean Unweighted and Weighted Seat Back Overall Rms Acceleration +/- One Standard Deviation

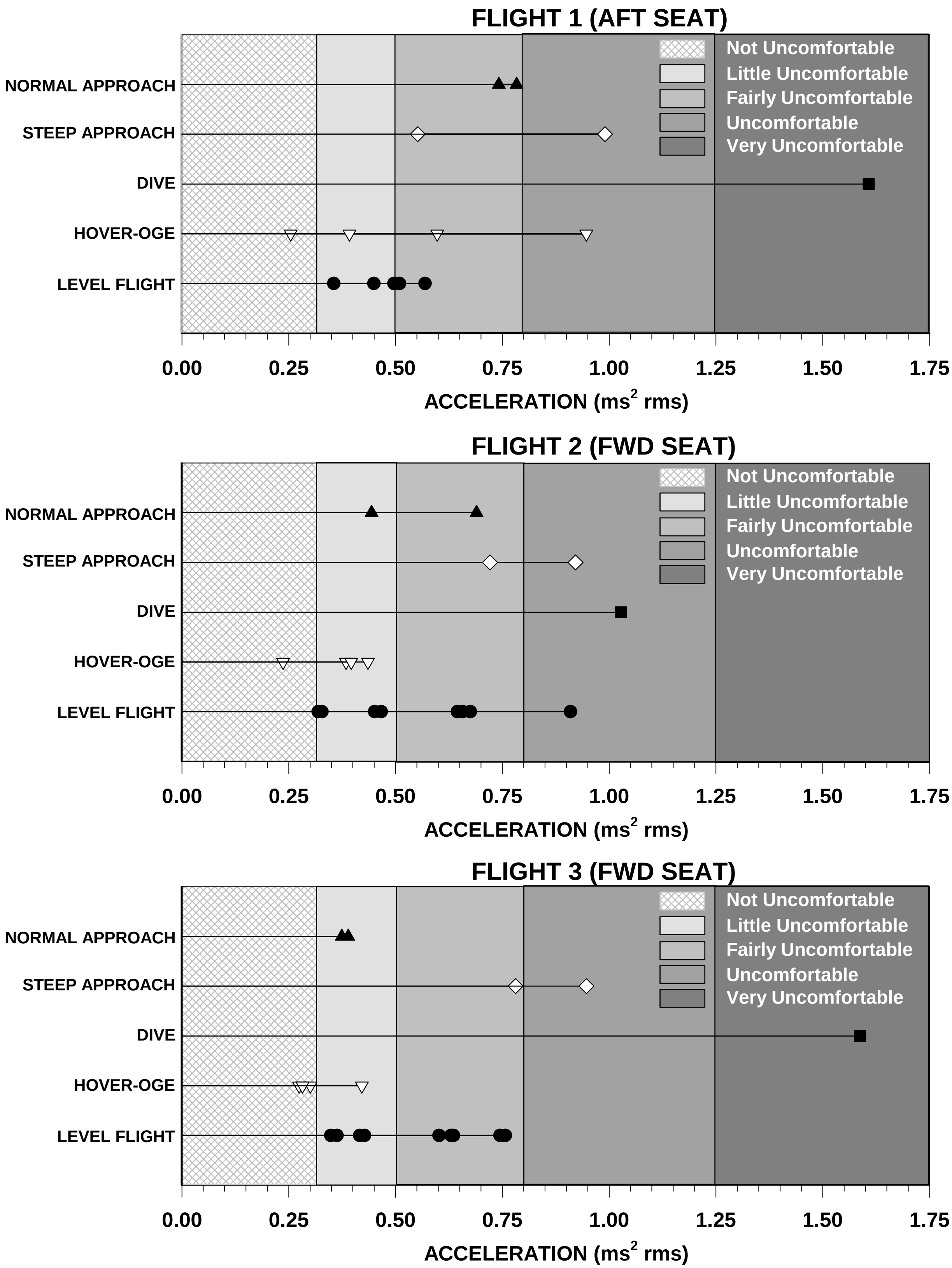


Figure B-7. Overall Vibration Total Values (VTVs) for Comfort for Selected Flight Conditions

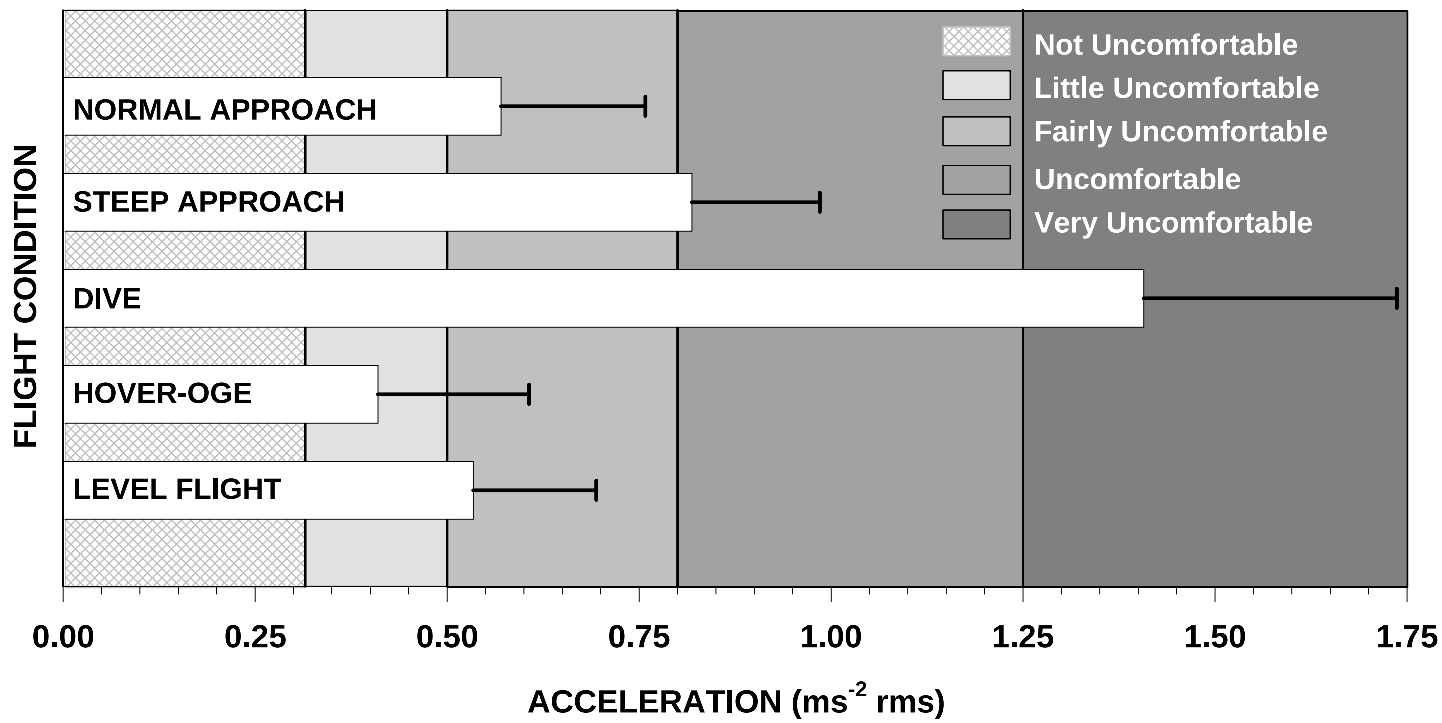


Figure B-8. Mean Overall Vibration Total Values (VTVs) for Comfort + One Standard Deviation Among All Three Flights

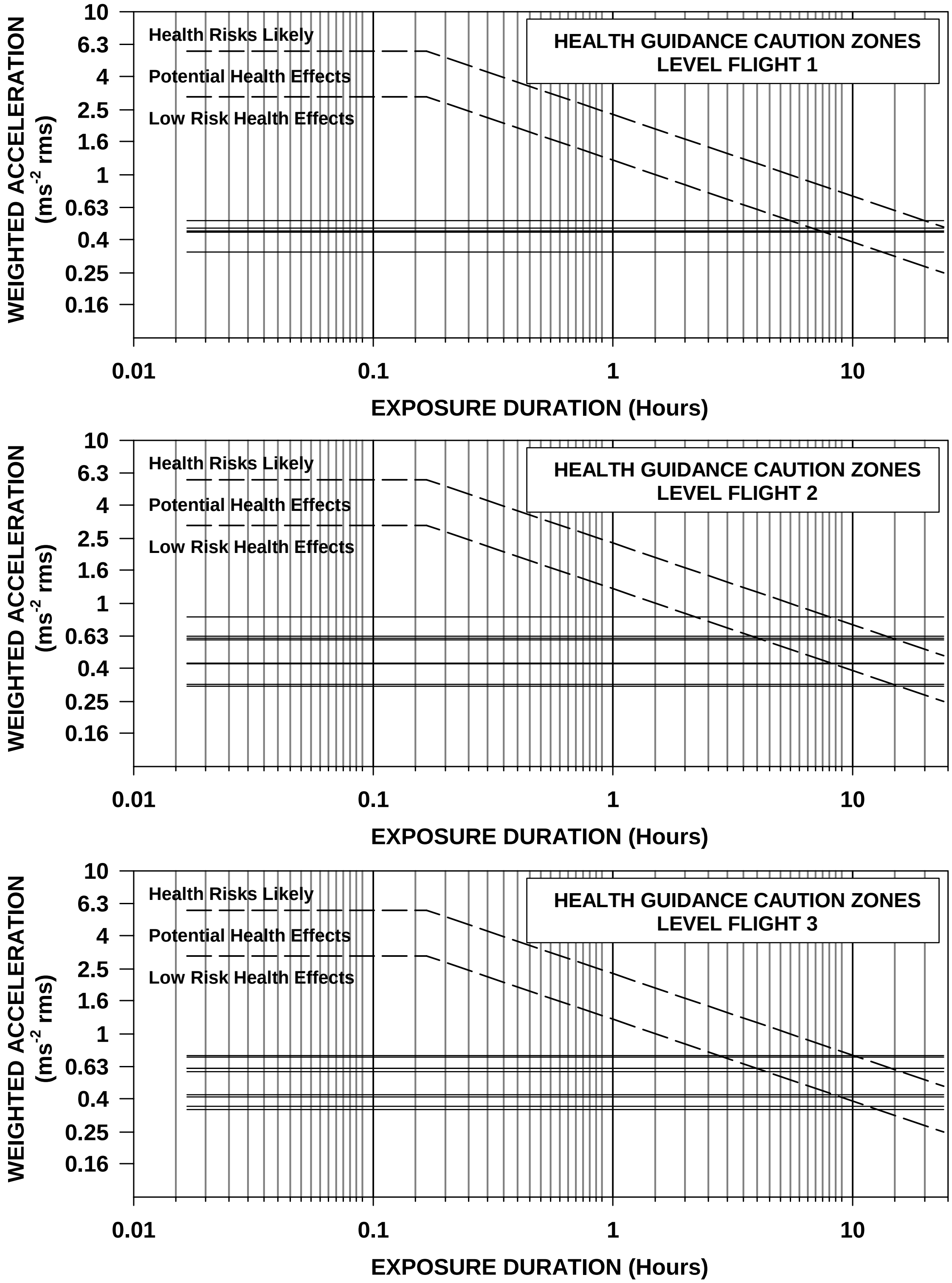


Figure B-9. Vibration Total Values (VTVs) for Health Risk - Level Flight

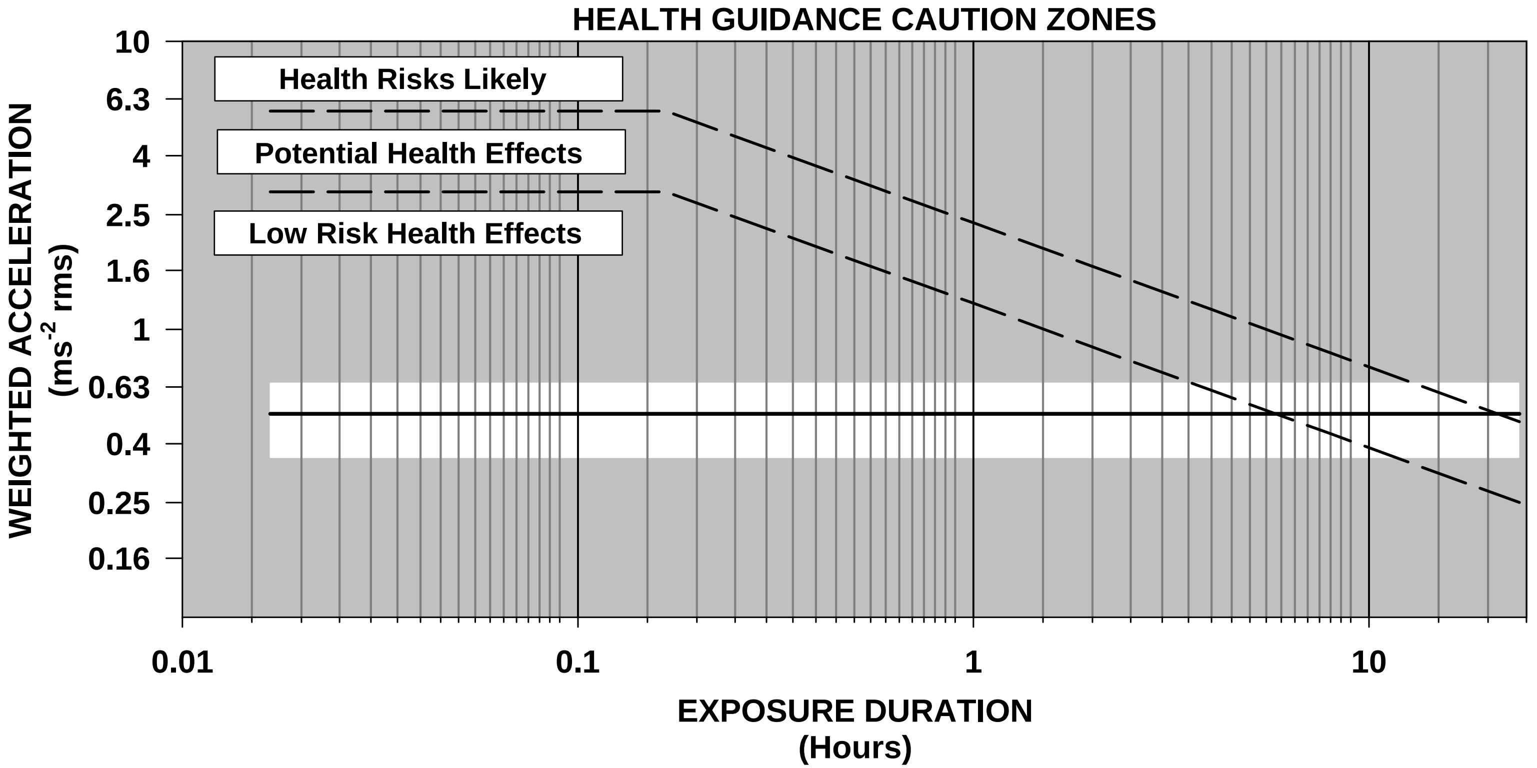


Figure B-10. Mean Vibration Total Values (VTVs) +/- One Standard Deviation - Level Flight

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23 April 12

MEMORANDUM FOR DTIC-OQ
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SUBJECT: Request to Change the Distribution Statement on a Technical Report

This memo documents the requirement for DTIC to change the distribution statement on the following technical report from distribution statement B to A. Approved for Public Release; distribution is unlimited.

AD Number: ADB313268
Publication number: AFRL-HE-WP-TR-2005-0114
Title: Super Cobra (AH-1Z) Human Vibration Evaluation

Reason for request: The information and representative data contained in this document are valuable resources for government, industrial, and academic institutions involved in the upgrade of subject equipment/aircraft, improvement of human interfaces (such as seating systems and helmet systems) to mitigate deleterious effects of equipment vibration on health and performance, equipment simulator development/enhancement, modeling of human response to equipment vibration, and the development/improvement of equipment design and exposure standards.

Donald Denio

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